

region. The particle surface must be of low polarity which is determined by elemental composition and/or structural bonding considerations. Water film instability at a hydrophobic surface arises not only from a disrupted interfacial water structure but also from a cavitation phenomenon which involves coalescence of nanobubbles in the interfacial water region. Such is the nature of the hydrophobic surface state.

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## Intensive Cells: Design

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## Introduction

In conventional flotation practice, the particles to be treated are dispersed in a suspension in water. Reagents are added to make the particles to be floated hydrophobic or nonwetting. The particles which are to be left behind remain in a wettable state. Air bubbles are then introduced into the slurry or pulp in a contacting device or cell, and collide with the non-wetted particles, carrying them to the surface where

they form a froth. The froth concentrate flows over a weir and out of the flotation cell, while the unwanted tailings flow out of the bottom.

The effectiveness of this type of cell lies in the ability of the bubbles rising in the liquid to collide with particles in suspension. Because the concentration or hold-up of air in the liquid is not very high – typically less than 10% by volume – the probability of a collision is correspondingly low. The low frequency of useful collisions between an individual bubble and the particles in a flotation machine can be overcome by increasing the residence time of the suspension. In this way, by using long residence times which can sometimes be as much as an hour in a

flotation bank, it is possible to achieve high recoveries of a floatable material.

In recent times, a number of flotation machines have been introduced which seek to reduce the residence time, by using new ways to bring about the contact between particles and bubbles. These are referred to as intensive flotation cells. Although the way in which the air is introduced – and the bubbles are made – differs from one type to another, they share a common feature. The collision between particles and bubbles does not take place within a liquid with a low number concentration of bubbles, or with a low gas hold-up. Rather, the air is introduced in such a way that contact is made in a device with a high air void fraction – a high ratio of gas volume to a given liquid volume. Once contact has been made, the bubbly mixture, which resembles a dense foam, passes to another vessel where the bubbles can disengage from the liquid, bearing their load of floatable particles to the supernatant froth layer.

The formation of bonds between bubbles and particles after collision is an essential step in flotation, and the topic has received much attention in flotation theory and practice. It has not always been appreciated that phenomena which take place in the froth phase above the liquid can also have a large effect on overall flotation performance. While the yield or recovery of floatable material obviously requires an efficient mechanism for contacting particles and bubbles, the grade or purity of the product is largely determined by froth-phase phenomena. When a continuous cloud of bubbles, whose surface contains selectively adsorbed hydrophobic particles, rises upwards through the froth-liquid interface, some of the liquid is trapped between the bubbles and is entrained into the froth layer. This liquid is the same composition as the main liquid in the flotation cell, so the concentration of gangue or waste particles in the liquid in the froth is approximately the same as in the liquid layer from which it arose, at least in the first instance. The presence of nonselective particles in the entrained water will reduce the grade of the concentrate product. While the bubbles are rising in the froth, the liquid layers between bubbles are draining, and gangue particles are carried downward, returning to the pulp layer. Over the last 20 years, it has become commonplace to apply clean water to the top of the froth layer, causing a continuous downward flow through the froth which tends to wash out the entrained gangue. With froth washing, flotation products of very high grade can easily be produced. (This assumes that the valuable material is completely liberated from the gangue by grinding. Any gangue which is locked into valuables

will generally float with the latter, thereby reducing the concentrate grade.)

The main objectives in the design of froth flotation equipment are always the same: to produce a device capable of achieving high grades and recoveries, with small size, minimum capital and operating costs, ease of operation and maintenance. To meet these objectives, many new cells have been tried over the years. This review will concentrate on the limited range of such cells which can genuinely be described as intensive, in that the contact time between bubbles and particles is very short, and the flotation cells are correspondingly quite small relative to the throughput. These are the air-sparged hydrocyclone (ASH), the Jameson cell, and the Ekof cell.

### The Air-Sparged Hydrocyclone

The ASH was invented by Professor Jan Miller of the University of Utah, and was patented in the USA in 1981. It makes use of the centrifugal forces which arise when air is sparged through the walls of a hydrocyclone. The device consists of a cylinder with a porous wall enclosed in an external chamber (**Figure 1**). The feed slurry enters tangentially through a conventional hydrocyclone header at the top of the cyclone, to form an annular liquid layer on the inner surface of the porous wall. The slurry moves downwards through the cylinder with a strong swirling motion. Bubbles are generated at the surface of the porous wall and, because of the swirling motion, bubbles which are produced on the porous surface experience an inwardly directed centrifugal force which carries them away from the wall, to pass quickly through the annular layer, collecting floatable particles on the way, forming a froth layer in the core of the cyclone. The froth leaves through the vortex finder in the top of the cylinder, while the tailing particles whose density is greater than that of water move towards the wall and are discharged through an annular gap in the bottom of the vessel.

An important feature of the ASH is the froth pedestal in the base. This stabilizes the froth and prevents it from passing out in the tailings. The froth zone is forced to move upwards through the vortex finder, carrying the hydrophobic particles. The hydrophilic particles are carried out in the tailings slurry.

The performance of the ASH is dictated by the fluid motion in the swirl layer adjacent to the porous wall, which in turn is controlled by the kinetic energy in the inflowing slurry, and the physical dimensions of the header and the vertical cylinder.

The bubble contact time in the hydrocyclone is of the same order as that of the pulp residence time, around 10 s. There is a correspondingly high capacity

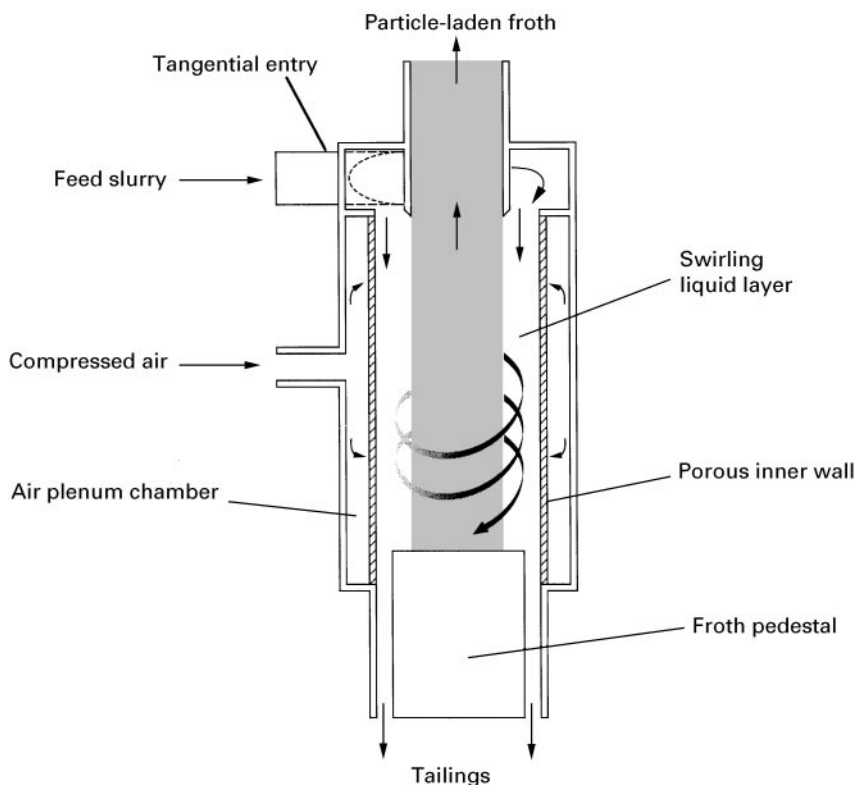


**Figure 1** Schematic of the air-sparged hydrocyclone.

per unit volume, which is of the order of 100–600 tons day<sup>-1</sup> ft<sup>-3</sup> of cell volume (3600–21 500 tonne day<sup>-1</sup> m<sup>-3</sup>) as against 1–2 tons day ft<sup>-3</sup> (35–70 tonnes day<sup>-1</sup> m<sup>-3</sup>) for mechanical cells and columns. To date, the cells are not very large, but the capacity is quite high. Thus an ASH of diameter 5 cm and height 50 cm has a capacity of 3–18 tpd of solids.

The feed enters at conventional hydrocyclone pressures of 5–25 psi (35–170 kPa) and the air is supplied at a relatively high pressure of around 65 psi (440 kPa), which is necessary to force the air through the porous wall at the required flow rate.

An important parameter which limits the performance of flotation cells is the superficial velocity  $J_g$ , which is the volumetric flow rate of the flotation air divided by the cross-sectional area of the pulp normal to the direction of the air flow. A high  $J_g$  will lead to a high concentrate production rate, other things being equal. In conventional cells, the only force acting on the liquid in the froth is that of gravity. Because of the centrifugal field in the ASH, the drainage force on the liquid in the froth is enhanced, and high  $J_g$ s are possible. Thus, the typical air velocity in an ASH is around 1 standard L min<sup>-1</sup> cm<sup>-2</sup> of cylinder wall, which corresponds to a superficial velocity  $J_g$  of 17 cm s<sup>-1</sup>. This figure may be compared with typical values for flotation columns, which are of the order of

0.5–4 cm s<sup>-1</sup>, and mechanical cells where the figure is generally lower still – around 1 cm s<sup>-1</sup>. The consequence is that the ratio of air-to-pulp flow rates can be very high, leading to high recoveries despite the short residence time. Reported values of the air-to-pulp ratio are as high as 16 : 1. In mechanical cells and flotation columns, the ratio is usually 1 : 1.

As far as contact between particles and bubbles is concerned, the ASH is clearly a very intensive flotation device. However, it is not so effective at handling the froth-phase requirements. Ideally, to obtain high grades, it is necessary to be able to apply clean washwater, which can drain through the froth and flush the gangue into the tailings stream, while leaving the hydrophobic material attached to the bubbles. For this to occur, the velocity at which water can drain through the froth under gravity must be greater than the superficial upward froth velocity in the core. Using published data, it is possible to calculate that the axial upward velocity of the froth core in an ASH is in the range 180–1300 cm s<sup>-1</sup>. The diameter of flotation columns is fixed to allow for froth washing and the maximum working superficial air velocity  $J_g$  is about 4 cm s<sup>-1</sup> – far below the values attained in the ASH. Evidently it is not possible to design an ASH which can allow both intensive contact between bubbles and particles, and effective control of the

froth to obtain high grades. Accordingly, the ASH is most effective in applications where grade is unimportant, and where high recovery is desired. It is not surprising that the first large scale applications have appeared in the paper industry, for the removal of toner particles from recycled paper.

## The Jameson Cell

The Jameson flotation cell was invented by Professor Graeme Jameson at the University of Newcastle, Australia, in 1986. It was developed to a practical reality at Mount Isa Mines, Mount Isa, Queensland, and was licensed to MIM Holdings of Brisbane in 1989. To date, there are 187 installations worldwide, in 19 countries. The cell is used for roughing, scavenging and cleaning, and also for removing oil haze from solvent extraction liquors. The distribution by field of use is coal 37%; copper 29%; other minerals 17%; and solvent extraction 17%.

In this cell, contact between particles and bubbles takes place in a dense foam which is produced in a vertical downcomer, as depicted in Figure 2. The pulp is introduced to the top of the downcomer as a confined liquid jet, and air is entrained into the feed and broken up into fine bubbles by the jet. A dense foam with a high void fraction is created in the

downcomer, creating a very favourable environment for collision of particles and bubbles. In fact, because of the high void fraction, of the order 50–60% by volume, the pulp is distributed in the form of thin liquid films between the bubbles, and collection occurs by migration of particles within the thin films, which are not much thicker than the diameter of the particles.

The dense mixture of bubbles and pulp discharges at the base of the downcomer, and the bubbles disengage from the pulp, rising into the froth layer. The bubble-free pulp discharges as tailings from the bottom of the cell. The froth behaves like that on top of a flotation column, in that grade and recovery can be strongly influenced by the froth depth and the application of washwater, and the upward superficial air velocity  $J_g$ . From the point of view of collection, the downcomer operates best when the ratio of air rate to feed rate is less than one-to-one on a volume basis.

The froth is treated much as in conventional columns. Washwater is usually applied if a high grade product is required. As with columns, when the air rate is altered, both steps in the flotation process – particle/bubble contact and froth entrainment – are affected. Thus an increase in air rate may cause an increase in recovery because more bubble surface area is created on which to capture particles, and because changes in the ratio of bubble to particle sizes will affect the probability of collision. At the same time, there may be an increase in entrainment of the gangue into the froth which may lead to a decrease in grade, unless steps are taken to remove the entrained gangue by changes in froth depth and washwater rate. Thus the optimum performance of the cell is related to the air superficial velocity,  $J_g$ .

The key features of the cell are:

1. The contacting environment is highly intensive, so that only short residence times are required. The total cell residence time is 1–2 min; the residence time in the downcomer is around 10 s. A short column is therefore produced which is ideal for retrofit, or installation in cramped headroom. The floor area is, however, similar to that required by conventional columns for the same throughput.
2. The bubbles formed by the impinging jet are very small, offering enhanced carrying capabilities for fine concentrate particles.
3. Air is drawn in from the atmosphere and no air compressor or blower is needed.
4. In the cleaning zone, with the use of washwater, the levels of concentrate grade approach the maximum levels possible.

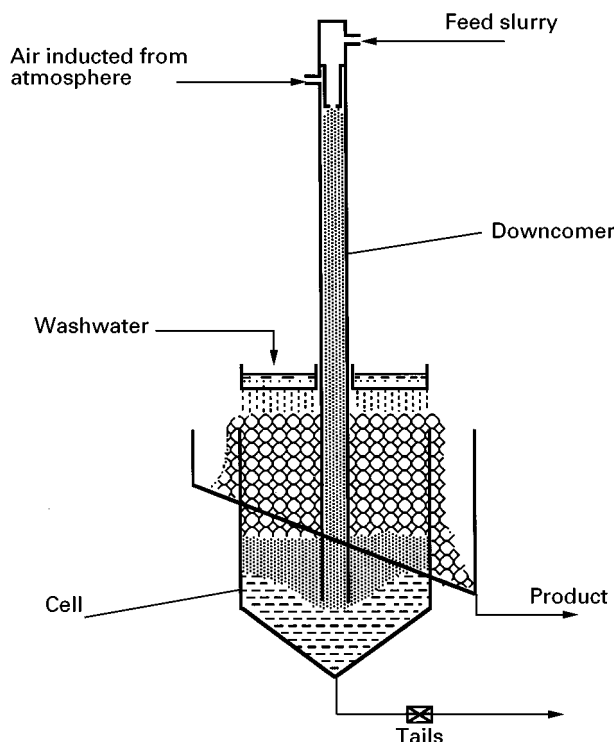


**Figure 2** Schematic of the Jameson cell. The height overall is approximately 2–3 m. The cross-sectional area of the cell is directly proportional to the desired feed flow rate.

The size of bubbles produced in the flotation cell is an important determinant of cell capacity. The mass of particles which can be carried out on the surface of the bubbles is dependent on the gas-liquid interfacial area. For a given gas flow rate, the interfacial area is inversely proportional to the bubble size, so there is an advantage in making small bubbles. However, it must be kept in mind that in the disengagement zone, the buoyancy of the bubbles must be sufficient to lift particles of the largest size in the pulp to the surface of the liquid. The best compromise appears to be to make bubbles in the range 0.35–1 mm. Bubble sizings on full scale operating cells and test cells show that the Jameson cell produces an arithmetic mean bubble diameter of the order of 300–600  $\mu\text{m}$ , while the Sauter (volume-to-surface) mean diameter,  $d_{vs}$ , is of the order 360–950  $\mu\text{m}$ . These sizings compare very favourably with conventional columns where the Sauter mean bubble size is typically 2–3 mm.

Some general operating characteristics of the Jameson cell are now discussed.

### Air Velocity in the Cell

The superficial gas velocity is the upward superficial velocity of air in a flotation cell, calculated by dividing the downcomer air rate ( $\text{cm}^3 \text{s}^{-1}$ ) by the cross-sectional area ( $\text{cm}^2$ ) of the riser part of the cell. The cell is normally circular or rectangular in section, and the appropriate cross-sectional area is simply the area normal to the direction of the flow of the froth, excluding the area occupied by the downcomer(s). The superficial velocity  $J_g$  is conveniently expressed in units of  $\text{cm s}^{-1}$  because values typically range from 0.5 to 4  $\text{cm s}^{-1}$  in practice.

The recovery and concentrate carrying rate ( $\text{g min}^{-1} \text{cm}^{-2}$ ) tend to increase with increasing  $J_g$ . As in conventional columns, there is a limiting upward flux of bubble surface through the pulp above which froth flooding occurs, resulting in the loss of froth-pulp interface, a very wet froth and total loss of selectivity. There is consequently a maximum air rate  $J_{g\text{max}}$  defined by this limiting flux and bubble size. In flooding, the entire cell fills with froth as the only stable phase, and there is no pulp phase.

The operating  $J_g$  used in the sizing of the Jameson cell depends strongly on the application, and on the residual reagent concentrations from any upstream processes. Generally speaking, low values ( $J_g = 0.4\text{--}0.8 \text{cm s}^{-1}$ ) are employed in cleaning applications, and high values ( $J_g = 1.0\text{--}2.0 \text{cm s}^{-1}$ ) are employed in roughing or scavenging applications.

In cleaning operations, a high proportion of the feed reports to the concentrate, and the froth loading tends to be high. Consequently, the bubbles are well

coated with particles, which tend to stabilize the froth by reducing the froth coalescence rate. The drainage rate of the interstitial liquid in the froth is retarded by the relatively high concentration of particles, which has the effect of increasing the apparent viscosity of the interstitial liquid. Accordingly, it is necessary to design for lower values of  $J_g$  to allow time for the gangue to drain from the froth to obtain the required high grade. In roughing applications, however, only a small fraction of the feed reports to the concentrate and the froths formed tend to be less stable as a consequence. Also, gangue entrainment is not such a serious problem, because it can be dealt with in the downstream cleaning circuit. As a consequence of the higher coalescence rate the froth bed is shallower than that of the cleaners and a lower froth residence time will give good drainage. It is therefore usual to design a Jameson cell for a roughing application with a higher  $J_g$  than in the cleaners.

In some circumstances, high residual concentration of reagents in the feed necessitates the use of low values of  $J_g$  to avoid froth flooding. Although frother concentration is of primary importance to bubble size and hence the advent of froth flooding, circumstances have arisen where collector and frother interaction has been observed. In such a case, the frother dose should be decreased if collector dose is increased, and vice versa. Too high a frother or collector concentration can lead to froth flooding while too low a dose can lead to loss of froth stability.

Particle size can also have an influence on the maximum  $J_g$ , due to its effect on froth stability through bubble-bridging. Small particles (less than 100  $\mu\text{m}$ ) are easily collected at low gas rates, while recovery of coarser particles may be assisted by higher rates.

A complex system of liquid and air recirculation patterns forms in the bottom of the cell. The cell design is based on downcomer flows and downcomer placement to optimize this system to produce best grade and recovery. There is no limit on cell volume, providing the net downwards velocity of pulp,  $J_L$ , is sufficiently low to avoid the entrainment of bubbles in the underflow. When the froth and disengagement zones have the same cross-sectional area, the two important velocities are the rate of rise of the bubbles in the pulp, and the rate of drainage of liquid in the froth. The former is usually greater than the latter, so that a column sized to give the correct  $J_g$  will also give the correct  $J_L$ , and bubble entrainment in the downward flow will not be a problem.

### Froth Depth

The froth phase in a Jameson cell can be controlled as in conventional columns. Shallow froth depths (less

than 200 mm) are used where high recovery is necessary and grade is of secondary importance, while deeper froths (up to 1 m) are employed to obtain maximum concentrate grade. Shallow froths result in significant entrainment of very fine ( $< 10 \mu\text{m}$ ) gangue mineral which accompany the pulp phase. With deeper froths, significant drainage of hydrophilic gangue will take place, producing a higher grade concentrate, and a higher percentage of solids in the concentrate. Under some circumstances, the addition of washwater to the froth will assist froth mobility, and assist an otherwise immobile froth to keep moving to the overflow lip.

### Air/Pulp Ratio

The air-to-pulp ratio (the ratio of the volumetric flow rates of air and pulp) in Jameson cells is usually in the range 0.3–0.9. Experiences with large (2–3 m diameter) Jameson cells indicate that operation at a low air/pulp ratio does not detract from metallurgical performance providing the superficial gas velocity  $J_g$  is maintained above  $0.4 \text{ cm s}^{-1}$ . Operation at lower air/pulp ratios has a stabilizing effect producing a finer, more uniform bubble size. A significant advantage of operation at lower air/feed ratios is that lower concentrations of frother are required.

The flux of interfacial area for a given gas rate varies directly as the gas flow rate and inversely as the bubble size. Thus the flux of bubble surface area, interfacial area per unit area of column cross-section per unit time, can be maintained with reduced superficial gas rate, providing the bubble size decreases accordingly.

### The Effect of Washwater

Clean water can be applied to the top of the froth, to flush entrained material downwards, preventing it from flowing out with the flotation product. There are two measures which are used to measure and control washwater addition: the bias and the washwater ratio.

Bias is the absolute excess of the washwater applied to the froth, over the quantity of water being recovered in the concentrate, expressed as a superficial velocity  $J_b$  ( $\text{cm s}^{-1}$ ):  $J_b = (Q_{\text{ww}} - Q_{\text{wc}})/A_c$ , where  $Q_{\text{ww}}$ ,  $Q_{\text{wc}}$  are the volumetric flow rates of washwater and water in concentrate, and  $A_c$  is the cross-sectional area of the column.

The washwater ratio is defined as the ratio of the washwater addition rate, to the flow rate of water in the concentrate:  $W = Q_{\text{ww}}/Q_{\text{wc}}$ . The washwater ratio is a relative measure of the amount of washwater applied. If no washwater is used, the washwater ratio is zero and the bias is negative. When  $J_b = 0$ ,  $W = 1$ .

A positive bias corresponds to washwater ratios greater than unity.

Although the bias does give an indication of the absolute amount of washwater being added, its use can be misleading because it does not take into account the wide variation in the absolute values of the rate of water entrainment in the concentrate. It is preferable to use the washwater ratio, which is a relative figure. In practice, it has been found that best performance is achieved when the washwater ratio is greater than 1.

### Scale-Up

Scale-up of the Jameson cell is relatively simple, since the flotation capacity is proportional to the cross-sectional area of the cell, and the flow capabilities of the downcomer. Downcomers range in size from 0.2 to 0.36 m, and a large installation will have multiple downcomers. Large cells are typically 5 m in diameter, with 12–16 downcomers, and handle flow rates of  $1200 \text{ m}^3 \text{ h}^{-1}$ . Extensive testing has shown that the results obtained in small test units, of diameter 0.3 m, give an accurate picture of the performance of a large cell on the same feed. In many cases, test work is not required, because of the availability of data from operational plants which will allow a design to be established for a new application with an ore of similar characteristics.

Because there is a limit on the amount of air which can be supplied to a given amount of feed slurry in the downcomer, the Jameson cell can become limited by carrying capacity. Thus, if there is an excess of particles in the feed above the mass which can be carried by the available surface area of bubbles, some of the hydrophobic material will not be transferred to the concentrate. In such cases, it may be necessary to install a second cell in series with the first, to ensure a high recovery of the values. An alternative which is increasingly being used is to recycle part of the tailings. The feed pump is then sized so as to be well above the normal operating capacity. The feed pump draws from a pump box in the circuit ahead of the Jameson cell, and receives flow from two sources: new feed and recycled tails. It has been found that the recovery with recycle in the range 30–50% of the feed flow rate is equivalent to the addition of a second cell in series.

### The Ekof Cell

The Ekof cell, also known as the Pneuflo cell is marketed by KHD Humboldt Wedag, of Bochum, Germany. It arose from a cell invented by Professor Albert Bahr, of Clausthal Technical University, Germany, in 1974. The Bahr cell consists of a vessel

of inverted conical form. The feed is premixed with air in a series of aerators distributed around the periphery of the vessel, in which air is injected through a porous wall into the transversely moving pulp. The bubbly pulp mixture is then fed to the vessel, where the bubbles rise and make contact with the floatable particles and carry them to the surface.

In the Bahr cell, the air-pulp mixture is introduced through pipes which enter through the wall of the vessel part-way up from the bottom of the cone, pointing vertically upwards to form a jet or plume. The jets are equispaced about the periphery of the cell. The idea was that a jet would spread out and mix with the pulp in the tank, bringing the bubbles into contact with the particles. Each jet would increase in area with vertical height, until at the surface the cross-sectional area of the jets would be about the same as that of the cell. The problem with this concept is that, as the size of the vessel and the design throughput increases, the height of the cell must increase as well. This difficulty was overcome in a later design in which the pipes delivering the air-pulp mixture are directed tangential to the cell wall, so that a low speed swirl develops. This design has been referred to as a Pneufлот cell. In both the Bahr and Pneufлот cells, the froth discharges over a lip into an annular launder which surrounds the vessel.

Because of the way the bubbles are generated, a high air pressure is needed to drive the air through the porous wall, and a relatively high feed pressure is needed to accelerate the pulp to the required speed in the aerator. In early models, froth washing was not provided, but it is available in later versions. The Bahr cell has had success especially in coal flotation.

In Pneufлот cells of the new form (Figure 3) the feed enters through a vertical pipe, and compressed air is introduced through small openings in an aerator unit at the top of the pipe. A model is also available in which the air is introduced into a Venturi. The aerated pulp is led through a central pipe to a low point in the flotation cell, and is diverted upwards by a distributor. The purpose of the distributor is to create an upward flow of bubbles which promotes flotation of coarse particles.

The latest form of Pneufлот cells is fitted with a froth crowder, which is of value when the loading of particles in the froth is low, and the froth is relatively unstable. The use of washwater is also possible in this design, as depicted in Figure 3.

Scale-up of the Pneufлот cell is not possible without testing on a pilot plant. There is no flotation time as in mechanical cells. The number of stages needed for a particular application can be determined by tests in which a Pneufлот cell is fed from an agitated tank at  $6\text{--}10 \text{ m}^3 \text{ h}^{-1}$ , with recycle of tailings from the cell

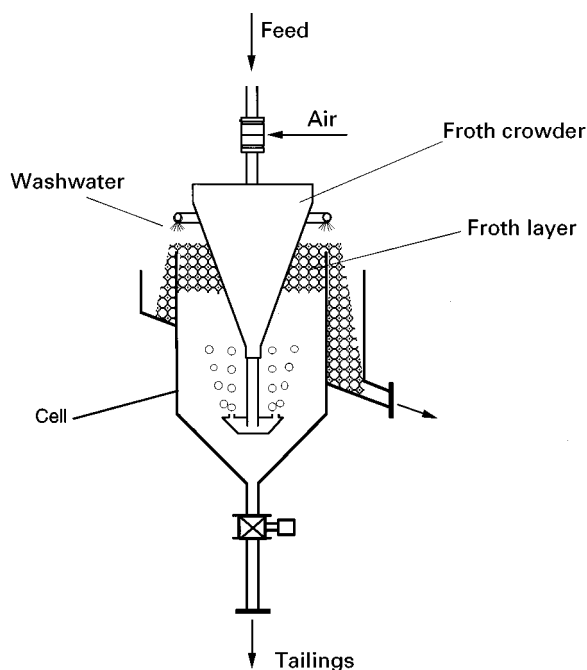


**Figure 3** The essential features of the Ekof or Pneufлот cell of the new form.

back into the tank. From a plot of the concentration of the element of interest in the froth concentrate, the feed and the tailings, all as a function of time, it is possible to deduce the number of stages required by a stepping procedure.

The Pneufлот cell is in use in a number of applications, on magnesite, copper, galenafluorite, etc.

## Future Developments

Further intensification of the flotation process is likely to come about in two directions. The processes of bubble contacting, bubble transfer to the pulp-liquid interface and froth drainage, are all responsive to a force field which can induce body forces on the liquid. In normal circumstances, the main body force is that of gravity. Accordingly, if the effective flotation rate per unit volume is to be increased, the logical step is to subject both the liquid and the froth to a centrifugal field. This will undoubtedly increase the mechanical complexity of the apparatus, and the saving in flotation cell volume may not warrant the extra cost of building, running and maintaining the equipment. Another possible direction for increased intensification is in the design of the initial gas-liquid contacting device. We have seen that, in both the Jameson cell and the Ekof cell, contacting takes place in a pipe or downcomer which must be of sufficient length to ensure efficient contact between bubbles and particles. It is likely that other

contactors could be devised which could bring about essentially instantaneous contact between particles and bubbles, effectively eliminating the down-comer. However, the over-riding objectives mentioned earlier – achieving high grades and recoveries, with small size, minimum capital and operating costs, in equipment which is easy to operate and maintain – will always remain the prime concerns of industrial users. In any new approaches, these objectives must be kept in view.

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## Oil and Water Separation

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## Development

The process of flotation needs a gas bubble to collide with, and attach to, an oil droplet; because of the hydrophobic nature of the oil droplet, a

stable gas–oil matrix is formed. The buoyancy of the oil droplet is increased by the attachment of the gas bubble, causing the oil droplet to rise rapidly through the water. Typically, one gas bubble will attach to one similar-sized oil droplet as described by Leech. As the bubbles in the froth phase burst, an oil layer is formed on the surface of the water. Oil and froth are then removed from the surface on an intermittent or continuous basis, depending on the mechanism used.